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13. ABSTRACT *(Maximum 200 words)*

Experimental and theoretical research has been carried out with the long term goal of producing nanostructures by passing an atomic beam through one or more standing wave optical fields. Theoretical estimates are consistent with the prospect of creating structures having periods on the order of tens of angstroms. During the final period of this grant, we have been able to demonstrate a de Broglie wave atom interferometer operating in the time domain. The interferometer was used to obtain preliminary measurements of $\hbar/m$ (m is the atomic mass) and the acceleration of gravity. The interferometer is novel in that it can operate on a single, nondegenerate ground state and relies *critically* on quantization of the atomic center-of-mass motion for its operation, in contrast to some other classes of atom interferometers. The experimental line shapes are in good agreement with theoretical predictions that incorporate subtle interference phenomena associated with phase gratings. The data provides indirect evidence for the existence of spatial harmonics in the atomic density having a period $\lambda/6$, where λ is the wavelength of the optical fields. A theory of Ramsey-fringe atom interferometry has been developed suggesting new experiments that could provide unprecedented accuracy for measurements of $\hbar/m$ and inertial effects.

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Atomic Interference in Standing Wave Fields

Final Progress Report

Paul R. Berman

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University of Michigan

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Statement of the Problem Studied

The long term goal of this project is to create nanostructures by passing a beam of atoms through two or more standing wave light fields. Following interaction with the standing waves, the atomic density contains all even harmonics of the standing wave light field. At appropriate distances following the interaction with the light fields the different harmonics are focused, enabling one to isolate each of the harmonics. By transferring the atomic density spatial distribution to a surface, one can create pure harmonic gratings having periods with periods as small as tens of angstroms. The research has both theoretical and experimental components. A detailed understanding of the scattering of atoms by standing wave fields is needed to properly model the experimental conditions. Scattering can occur in either the classical domain where the atoms' center-of-mass motion can be treated classically or in the quantum domain, where it is necessary to quantize the atoms' center-of-mass motion.

Summary of Important Results

Many of the results have been discussed in the Annual Reports covering the first two years of the grant. The topics in this Final Report will be restricted to results obtained subsequent to those reports.

Time-domain de Broglie Wave Atom Interferometer. Perhaps the most significant result in this period is the demonstration of a de Broglie wave atom interferometer operating in the time domain [16] (numbers refer to items in the *List of Publications).* Atoms in a magneto-optical trap are subjected to two, off-resonant standing wave pulses of radiation, having wave length λ. The first pulse acts as a phase grating for the atoms, creating an atomic wave function which is a phased superposition of all even harmonics of the radiation field. As time evolves, the atom phase grating is converted to an amplitude grating, which quickly washes out owing to the Doppler effect. The second laser pulse starts a rephasing process, leading to a focussing of different spatial harmonics of the atoms at different times following the second pulse. The experiment monitors the second spatial harmonic which rephases at times $2T$, $3T$, $4T$, etc. The existence of the rephased harmonic at nT is indirect evidence for the existence of atomic spatial harmonics having period $\lambda/(2n)$ in the time between 0 and T.

Experimental results in good agreement with theory were obtained and the rephased signals at $t = 2T, 3T$, and $4T$ were observed. This indirect evidence for higher spatial harmonics is critical to the next stage of the experiment when the atoms in the cell are replaced by an atomic beam traversing two standing-wave fields. Apart from the implications for nanotechnology, the results of this experiment are of intrinsic interest. The experiment was carried out with pulse separations $T > \omega_\kappa^{-1}$, where $\omega_\kappa = \hbar\kappa^2/(2m)$, $\kappa = 4\pi/\lambda$, and m is the atomic mass. As such, this experiment depends *critically* on the quantum properties of the center-of-mass motion. Moreover, the experiment uses atoms that are effectively in a single ground state, making the results insensitive to stray light shifts. The atom interferometer has potential for high precision measurements of $\hbar/m$, rotation rates, and the acceleration of gravity. Preliminary measurements of $\hbar/m$ and the acceleration of gravity were obtained.

Experiments were also performed in room temperature vapor cells to study both collisional and transit time effects. The experiments are potentially among the most sensitive for measuring very small velocity changes.

Ground State Ramsey Fringes. It is possible to combine the Ramsey fringe techniques and those of atom interferometry to design experiments that have an unprecedented accuracy for measurements of $\hbar/m$ and inertial effects. We have developed a theory for such experiments [14] and compared the sensitivity to other atom interferometric measurements of these quantities. It seems that it may be possible to increase the accuracy by two or three orders of magnitude to levels

that are competitive with current state-of-the-art measurements of $\hbar/m$, rotation rates, and the acceleration of gravity. We also predict a modification of ω_κ that can result from inertial effects.

Recoil-Induced Effects. In pursuing our understanding of the role played by quantization of the atomic center-of-mass motion in the spectroscopic response of atoms, we have investigated two classes of atom-field interactions. First, we have looked at Bragg scattering of atoms by radiation fields from a somewhat different point of view [12]. A beam of atoms passes through a traveling wave pump field and one or more counterpropagating probe fields. The interaction time is sufficiently long to be in the Bragg scattering regime. We have shown that this problem can be viewed as an effective two, three or multilevel atom problem in which the atoms interact with two or more radiation fields. As such, the theory closely resembles that of the pump-probe spectroscopy of a two or multi-level system. We have also looked at the somewhat unusual gain properties of the fields produced by their interaction with the atoms.

The second calculation related to atomic recoil involves the excitation exchange between two identical atoms [15]. We have shown that for separations greater than the optical wave length associated with a ground to excited state transition, the atomic recoil can be viewed in a "step-wise" fashion - one atom emits radiation and recoils while the second scatters the radiation with a correlated recoil of its own. For separations less than the optical wave length associated with a ground to excited state transition, the atoms recoil as a composite system.

Miscellaneous. A calculation of transit time effects in coherent transient spectroscopy was carried out for arbitrary field strengths of the light pulses [10]. It was shown that previous treatments of this problem were in error. Our results were used to fit some of the interferometric data alluded to above.

An extensive analysis of scattering of atoms by microfabricated structures was published [11]. The Talbot, Talbot-Lau, and classical scattering regions were studied in detail, with many new analytical results obtained. A new effect, related to the generation of atomic spatial harmonics having period $\lambda/4$, was shown to arise for scattering of a *thermal* beam of atoms.

An amplitude calculation of lasing without inversion was carried out in a dressed-atom basis to identify the underlying physical mechanisms responsible for this process [13]. In this picture, it is easy to identify the role that entangled states of the atom-field system play in determining the atomic response. Specific paths in the calculation can be correlated with the emission of specific modes of the vacuum radiation field.

Again using an amplitude approach, we have reexamined the excitation exchange between identical atoms [17]. Atom 1 is excited at $t = 0$ and atom 2 in its ground state. What is the earliest time that atom 2 can be excited by excitation exchange? There has been some controversy over this question. We have shown that the probability that atom 2 is excited is identically zero for $t < R/c$, provided one retains only those terms which depend on the interatomic separation R. On the other hand the *joint* probability that atom 2 is excited and atom 1 in its ground state is nonvanishing for $t < R/c$. The implications of these results were discussed [17].

List of Publications

1. P. R. Berman, "Collisional Decay and Revival of the Grating Stimulated Echo," Physical Review A **49**, 2922-2932 (1994).

2. B. Dubetsky and P. R. Berman, "Magnetic Grating Free Induction Decay and Magnetic Grating Echo Using Ultrafast Excitation Pulses," Applied Physics (Germany), **B** 59, 147-157 (1994).

3. B. Dubetsky and P. R. Berman, "Creating and probing subwavelength atomic gratings using spatially separated fields," Phys. Rev. A **50**, 4057-4068 (1994).

4. B. Dubetsky and P. R. Berman, "Soft $X-ray$ amplification via resonant backward scattering from relativistic particle beams," Phys. Rev. Lett. **74**, 3149-3152 (1995) .

5. P. R. Berman, B. Dubetsky and J. Guo, "Recoil-induced resonances in pump-probe spectroscopy," Phys. Rev. A **51**, 3947-3958 (1995).

6. B. Dubetsky and P. R. Berman, "Recoil-induced optical Faraday rotation," Physical Review A **52**, R2519-R2522 (1995).

7. B. Dubetsky and P. R. Berman, "Atom-field interactions: Density matrix equations including quantization of center-of-mass motion," Phys. Rev. A **53**, 390-399 (1996).

8. P. R. Berman, B. Dubetsky and J. Guo, "Recoil-induced resonances in pump-probe spectroscopy," in *Coherence and Quantum Optics IV*, edited by J. Eberly, L. Mandel and E. Wolf, (Plenum, New York, 1996) pps. 525-526.

9. B. Dubetsky and P. R. Berman, "Recoil-induced optical Faraday rotation," in *Coherence and Quantum Optics IV*, edited by J. Eberly, L. Mandel and E. Wolf, (Plenum, New York, 1996) pps. 383-384.

10. J. L. Cohen and P. R. Berman, "Transit time effects in coherent transient spectroscopy," Phys. Rev. A **54**, 5262-5274 (1996).

11. B. Dubetsky and P. R. Berman, "Atom interference using microfabricated structures," in *Atom Interferometry*, edited by P. R. Berman (Academic Press, Boston, 1997) pps. 407-468.

12. P. R. Berman and B. Bian, "Pump-probe spectroscopy approach to Bragg scattering," Phys. Rev. A **55**, xxx-xxx (1997).

13. J. L. Cohen and P. R. Berman, "Amplification without inversion: Understanding probability amplitudes, quantum interference, and Feynman rules in a strongly driven system," Phys. Rev. A **55**, 3900-3915 (1997).

14. B. Dubetsky and P. R. Berman, "Ground state Ramsey fringes," Phys. Rev. A **xx**, xxxx-xxxx (1997).

15. P. R. Berman, "Resonant interaction between identical atoms including recoil," .Phys. Rev. A **55**, xxxx-xxxx (1997).

16. S. B. Cahn, A. Kumarakrishnan, U. Shim, T. Sleator, P. R. Berman and B. Dubetsky, "Time domain de Broglie wave atom interferometry," Phys. Rev. Lett., submitted (1997).

17. B. Dubetsky and P. R. Berman, "Causality in the excitation exchange between identical atoms," Phys. Rev. A **55**, xxxx-xxxx (1997).

Personnel

Scientific personnel working on this project and degrees awarded during this report period:
At the University of Michigan:
P. Berman (Principal Investigator)
B. Dubetsky (Assistant Research Scientist)
J. L. Cohen (Graduate Student)
D. Manna (Graduate Student)

At New York University:
T. Sleator (Principal Investigator for experimental work)
A. Kumarakrishnan (Postdoctoral Student)
S. Cahn (Graduate Student - PhD Degree awarded by SUNY-Stony Brook in Spring, 1997)
U. Shim (Graduate student)

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